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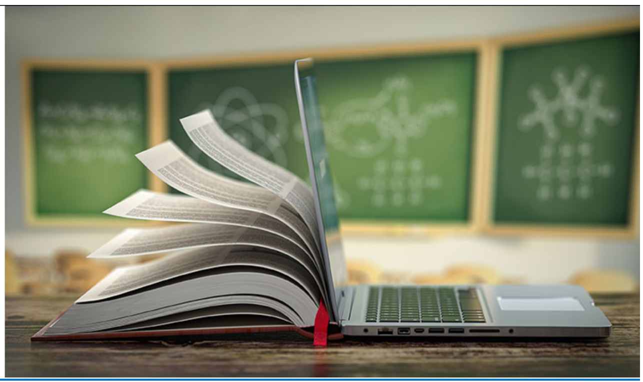

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Features of thermomechanics of pulsating gas flows in intake systems with grooves in relation to turbocharged engines

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Abstract. Reciprocating engines (RICE) are widely used as heat engines to convert the chemical energy of fuel into mechanical work on the crankshaft. Aerodynamic and thermophysical processes in gas exchange systems significantly affect the efficiency of internal combustion RICEs. This article explores the possibility of influencing the gas dynamics and heat transfer of pulsating gas flows in the intake system by placing a channel with grooves. It is known that the presence of grooves in the channel leads to the formation of significant secondary vortices, which radically change the physical picture of the gas flow. The studies are carried out on a laboratory bench, which was a single-cylinder model of a turbocharged RICE. The system of measurements of basic physical quantities is described, taking into account their high dynamics in gas exchange systems. The experimental data processing techniques are presented. Primary data on the instantaneous values of the gas-dynamic and heat-exchange characteristics of pulsating flows are reported. It is established that the presence of a channel with grooves in the intake system leads to a decrease in the turbulence number by 40% and the intensification of heat transfer in the range of 5-50% compared with the basic intake system. A positive effect is shown in the form of an increase in engine power by 3% when using an upgraded system.

1. Introduction

Reciprocating internal combustion engines (RICE) are the most common batch devices that are designed to convert the chemical energy of the fuel into mechanical work on the crankshaft. RICEs are widely used in industry as power plants. It is known that the engine largely determines the effectiveness of the technical product on which it is installed. Therefore, the improvement of engines remains an urgent task in the development of energy and engineering. It is known that the design and performance indicators of a gas exchange system significantly affect the performance of RICEs [1, 2]. Thermophysical processes in these systems determine the mass flow of air, air heating, thermal stresses in parts, etc. For example, scientists managed to reduce fuel consumption and improve the environmental performance of engines by improving the design of intake and exhaust pipelines [3-5]. In turn, other specialists also increased engine efficiency and reduced the amount of harmful emissions in exhaust gases by using various technical devices in gas exchange systems (combined cycles, cogeneration, thermoelectric generator) [6-8]. There are also studies on configuring the supercharging system of RICEs in order to improve their efficiency and reliability [9-11].

An effective way to influence the gas dynamics and heat exchange of air flows for various applications is known to consist in applying grooves or holes of different geometries to the heat exchange surface [12-14]. The presence of grooves leads to the formation of strong secondary flows behind them, which significantly intensify heat transfer with a slight increase in hydraulic resistance.

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The hypothesis of this study was to evaluate the effectiveness of the use of grooves in the gas exchange systems of RICEs in order to control thermophysical processes and improve their efficiency.

Thus, the objectives of this study are to study the effect of the presence of a channel with grooves on gas dynamics and heat transfer of pulsating gas flows in the intake system of a reciprocating engine, as well as to evaluate the positive effects for RICE from modernization of the system under consideration.

2. Research stands and task description

Gas dynamics and heat transfer studies of pulsating gas flows in the intake system were carried out on a single-cylinder engine model (Figure 1), equipped with a turbocharger-based supercharging system. The engine crankshaft was driven by an electric motor. The turbocharger rotor was driven by supplying compressed air from an external source to the turbine blade of the TC. The range of variation of the crankshaft rotational speed n of the installation was 600-3000 rpm, and that of the rotor of the turbocharger n_{TC} was 25000-55000 rpm. During the experiments, the following values were measured: 1) air pressure at the turbine inlet (pressure gauge); 2) the rotational speed of the TC rotor n_{TC} and the crankshaft n of the RICE (tachometers); 3) instantaneous values of velocity w_x (constant-temperature hot-wire anemometer), pressure p_x (high-speed pressure sensor) and flow temperature T (thermocouples) in the engine intake channel; 4) the local heat transfer coefficient α_x in the intake channel (a thread sensor of the hot-wire anemometer – Reynolds analogy). For more detailed methods for determining physical quantities, see [15].

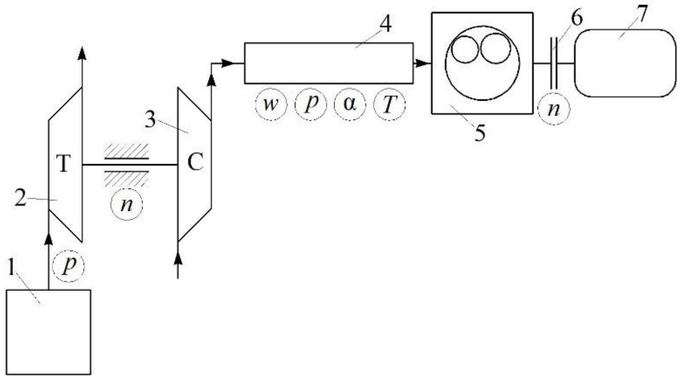

Figure 1. The layout of the experimental stand and the location of the sensors: 1 – a source of compressed air to drive the TC rotor; 2 – TC turbine; 3 – TC compressor; 4 – intake pipe; 5 – single cylinder reciprocating engine model (8.2/7.1); 6 – coupling; 7 – an electric motor for driving a crankshaft; p – pressure sensor; n – speed sensor; w – gas flow rate sensor; T – temperature sensor; α – sensor for measuring the local heat transfer coefficient.

Based on the obtained data, the air flow Q through the engine intake system, the turbulence number Tu_c of flow per engine operating cycle, and the heat transfer coefficient $\overline{\alpha_c}$ averaged over the engine operating cycle were determined. Air flow was determined by integrating the characteristic $w_x = f(\tau)$ for the period of the intake process and then multiplying it by the number of cycles corresponding to $n/2$. The turbulence number Tu_c was determined as the ratio of the RMS pulsation component of the flow velocity to the average value of the flow velocity in the channel. Averaging the flow rate for calculating Tu_c was carried out for one engine operating cycle (i.e., for two crankshaft revolutions). The heat transfer rate $\overline{\alpha_c}$ was determined by integrating the dependence $\alpha_x = f(\tau)$ also in one working cycle.

Research was conducted for two configurations of the intake system. The base channel had an inner diameter of 42 mm (length - 150 mm). The total length of the intake system was 450 mm. The modified channel had grooves on the inner surface (Figure 2). The grooves were oval in shape with dimensions of 2.5x5 and a depth of about 1.65 mm. The grooves were staggered in three rows.

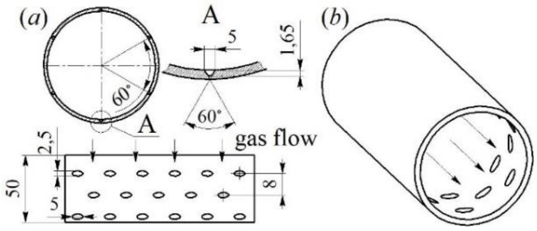

Figure 2. The geometric dimensions of the grooves in the intake pipe (*a*) and the isometric view of the channel (*b*).

The scientific hypothesis of using grooves in the intake system of a RICE with a turbocharger was to turbulize the flow, thereby improving heat exchange, which should lead to some cooling of the air and an increase in mass flow, and consequently, an increase in engine power.

3. The main results of experimental studies

The primary data on the measurement of physical quantities in the base inlet channel and the channel with grooves are presented in Figure 3.

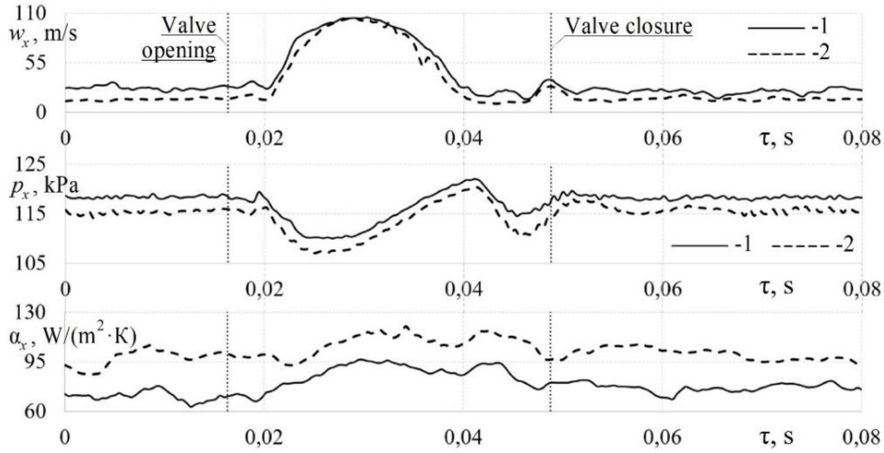

Figure 3. Dependences of the local flow velocity w_x and pressure p_x of the flow, as well as the local heat transfer coefficient α_x in time for the base intake system (1) and the intake system with a channel with grooves (2) for n = 1500 rpm and $n_{\text{тс}}$ = 46000 rpm.

It can be seen from the figure that the presence of grooves in the channel has an insignificant effect on the dependence $w_x = f(\tau)$. This is due to the fact that the sensitive element of the hot-wire anemometer sensor was located approximately in the center of the channel, and the flow turbulence through the grooves takes place near the walls of the pipeline. The presence of grooves in the channel has a more significant effect on the dependence $p_x = f(\tau)$. There is a noticeable decrease in the pressure in the inlet channel by 5-7% during the entire operating cycle compared to the base system. This indicates a slight increase in the aerodynamic drag of the system in the presence of a channel with grooves. The grooves have the greatest influence on the dependence $\alpha_x = f(\tau)$. There is a significant increase in the local coefficient (on average by 22%) compared with the base system. This is due to the vortex mechanism of heat transfer enhancement through the grooves mentioned above. This mechanism is associated with significant secondary flow velocities that the grooves generate. These secondary flows determine a slight increase in the aerodynamic drag of the intake system.

The turbulence numbers for the engine operating cycle were calculated for the basic and upgraded intake pipeline at different speeds of the TC rotor and the RICE crankshaft (Figure 4).

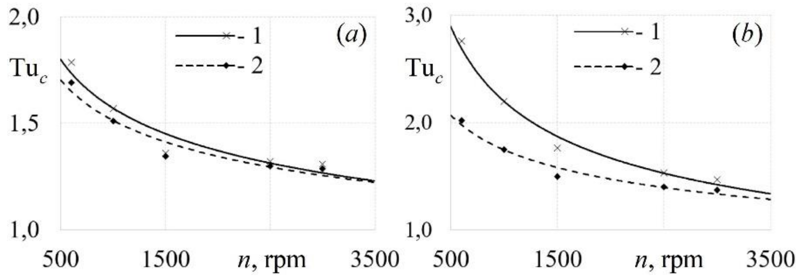

Figure 4. Dependences of the turbulence number Tu_c on the engine speed n for the base intake system (1) and the intake system with a channel with grooves (2) for different n_{TC}: a – 30000 rpm; b – 50000 rpm.

It can be seen from the figure that the presence of grooves in the intake channel does not actually affect the turbulence of the flow core at low rotational speeds of the TC rotor (differences in the Tu_c do not exceed 5%). Moreover, the differences in the values of the turbulence number increase with increasing n_{TC}. It has been found that the presence of grooves in the engine intake channel leads to a decrease in the turbulence number up to 40 % at high frequency n. This can have a positive effect on the degree of filling of the cylinder with air, since it is known that the stabilization of the pulsating flow contributes to an increase in the filling coefficient of the engine [16]. It should also be noted that the values of the Tu_c become practically the same at high engine speeds (the difference does not exceed 3%), which is typical for all turbocharger rotor speeds. In this case, the use of the intake channel with grooves does not actually affect the flow characteristics through the engine intake system (differences are within ± 6%). This confirms the observation that the presence of grooves in the hydraulic system does not lead to a noticeable increase in aerodynamic drag and does not impair the flow characteristics.

The influence of the presence of a channel with grooves on the heat transfer intensity in the intake system of the engine can be seen in Figure 5.

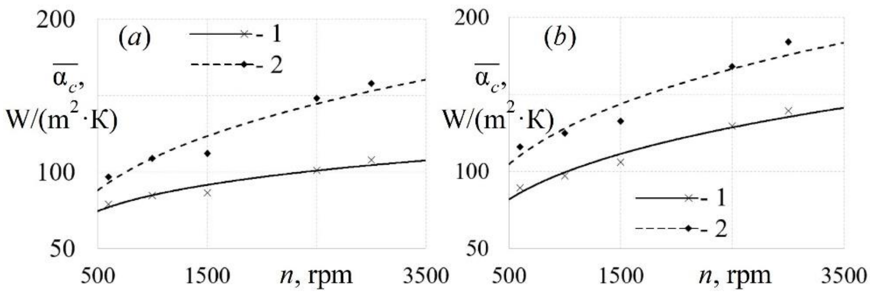

Figure 5. Dependences of the heat transfer coefficient $\overline{\alpha_c}$ averaged over the operating cycle on the engine crankshaft speed n for the base intake system (1) and the intake system with a channel with grooves (2) for different n_{TC}: a – 30000 rpm; b – 50000 rpm.

It has been found that the use of an intake channel with grooves leads to an intensification of heat transfer in the system under consideration up to 50% compared with the basic intake system. This is characteristic of all investigated operating modes of the RICE and TC. The physical mechanism of the growth of the heat transfer coefficient in the case under consideration has been described above.

An analytical assessment of the potential positive effect of modernizing the intake system was carried out; i.e., the filling factor and power were calculated for a two-cylinder gasoline engine with a basic intake system and a system with a channel with grooves. It has been found that the filling coefficient will increase by about 3.59% due to a decrease in air heating during cylinder filling and a slight increase in air density. This, respectively, will lead to an increase in the power of the RICE in question by 2.87%.

Conclusions

Based on the data presented in the article, the following conclusions can be drawn.

1. A laboratory bench has been developed that simulates physical processes in a turbocharged RICE, and a measurement system has been selected for studying gas dynamics and heat transfer of pulsating gas flows in the intake system of the reciprocating engine.

2. It has been established that the presence of a channel with grooves in the intake system leads to the following changes in gas dynamics and heat exchange of flows as compared with the basic intake system: 1) reduction in the turbulence number of up to 40% at high rotational speeds of the TC rotor; 2) the intensification of heat transfer in the range from 5 to 50% in the entire investigated field of the operating modes of the RICE and TC.

3. The potential positive effect of using an intake system with a channel with grooves in a gasoline engine is calculated. The maximum increase in power can be up to 3%. Data on thermophysical processes in hydraulic systems with different geometries expand the knowledge base and can also find practical application in the design of gas exchange systems for turbo-piston RICEs.

Acknowledgments

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